A comparative study of angle dependent magnetoresistance in [001] and [110] $La_{2/3}Sr_{1/3}MnO_3$

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Abstract

The angle dependent magnetoresistance study on [001] and [110] $La_{2/3}Sr_{1/3}MnO_3$ thin films show that the anisotropy energy of [110] films is higher when compared with a [001] oriented $La_{2/3}Sr_{1/3}MnO_3$ film of similar thickness. The data has been analyzed in the light of multidomain model and it is seen that this model correctly explains the observed behavior.

Key words: Magnetoresistance, LSMO, anisotropy
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1 Introduction

Double exchange pervoskite manganites, such as $La_{2/3}Sr_{1/3}MnO_3$ (LSMO), show colossal magnetoresistance[1] and have $\sim 100\%$ spin polarization[2,3]. Hence, this material forms an excellent candidate for studying spin polarized quasi particle injection in various types of systems. Secondly, the fact that magnetoresistive materials have immense technological application, it is essential to understand the underlying principles of the plethora of extraordinary phenomena seen in this class of materials. The exact microscopic mechanism for very large magnetoresistance(MR) is not very well understood in these systems.

In this paper a careful study of magnetoresistance as a function of angle between applied field and current direction in [001] and [110] epitaxial films of

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La$_{2/3}$Sr$_{1/3}$MnO$_3$ is reported. In both the cases MR at 10K and 300K was measured. While hysteresis in resistivity at 10K is seen for both films, at 300K only [110] films show hysteresis. This clearly demonstrates that the anisotropy energy of [110] films are larger than that of [001] films. Arguments and explanation of the observed data is based on the multidomain model given by O'Donnell *etal*[4].

2   Experimental Details

Thin epitaxial films of La$_{2/3}$Sr$_{1/3}$MnO$_3$ were deposited on [110] and [001] oriented SrTiO$_3$(STO) substrates using a multitarget pulsed excimer laser [KrF, $\lambda = 248$ nm] ablation technique. The deposition temperature (T$_d$), oxygen partial pressure pO$_2$, energy density (E$_d$) and growth rate (G$_r$) used for the growth of 150 nm thick layers were, 750^0 C, 0.4 mbar, $\sim$2J/cm^2 and 1.3Å/sec respectively. To fully oxygenate the samples, the deposition chamber was filled with O$_2$ to atmospheric pressure immediately after the growth and then the sample was cooled from 750^0 C to room temperature. Epitaxial growth in two sets of films with [110] and [001] directions normal to the plane of the film was established with X-ray diffraction measurements performed in the $\theta - 2\theta$ geometry. The measurements of resistivity as a function of temperature, magnetic field strength and the angle between field and current were done using a 4.2K close cycle refrigerator with a fully automated home made setup for applying fields at varying angles between 0 and 2π with respect to the direction of current[5]. The sample was mounted in way to keep the field in the plane of the sample for all angles of field. The room temperature resistivity of these samples is in the range of $\sim 2.7 - 2.8$ mΩ−cm. Isothermal hysteresis loops were measured for both the samples using a commercial magnetometer (Quantum Design MPMS XL5 SQUID) by applying field at various angles in the plane of the film. For the measurement of magnetoresistance in four probe configuration films were patterned in the form of a $1000 \times 100 \mu m^2$ bridge with photolithography and wet etching such that the long axis of the bridge was parallel to [001] and [100] direction for the [110] and [001] oriented films respectively. The [001] and [110] films were first characterized using a SQUID magnetometer to determine the easy axis . The data for such measurements have been published elsewhere[6].

3   Results and Discussions

In fig. 1 the R(H)/R(0) vs. H data for the [110] sample at 10 K (left panel) and 300 K right panel) taken at various angles between the applied field and

the current direction is shown. The current in this case was flowing along the easy axis [6] and the hard axis was in-plane and 90^0 to the current direction. Arrows in the figure mark the trajectory followed by the resistance as the field was swept from positive to negative extremities. At 10 K, the resistance increases superlinearly as the field is reduced from 700 Oe till it reaches a critical negative value H_c. On increasing the field further in the reverse direction, the resistance drops, first rapidly and then gradually. The resistance profile during $-H_{max}$ to $+H_{max}$ field sweep is a mirror image of the $+H_{max}$ to $-H_{max}$ sweep. A large hysteresis is evident in the figure whose area increases with the angle θ between $\vec{H}$ and $\vec{I}$. However the critical field $\pm H_c$ remains the same for all angles within the experimental error (± 10 Oe), and also compares well with the coercive field deduced from the M-H loop[6]. For the measurement performed at 300 K, the R(H) curve is mostly reversible except for a narrow range of the field between $\pm H_c$ where twin peaks appear in the resistance for non-zero values of θ. The reversible part shows a $\rho \propto H^\tau$ dependence with τ nearly independent of the angle θ.

The isothermal magnetoresistance at different angles between $\vec{I}$ and $\vec{H}$ for films with [001] orientation is shown in fig. 2 for measurement performed at 300 K (right panel) and 10 K (left panel). The current in this case was flowing along the hard axis and the easy axis [6] was 45^0 to the current direction. At 10 K and $\theta = 0^0$ the R(H) curve is mostly reversible except for the twin peaks appearing at $\pm H_c$ which agrees with the coercive field deduced from M-H measurements. On increasing the angle θ (moving away from the easy axis), two interesting features emerge from the data. First, the critical field at which the resistivity drops precipitously shifts to higher values and second, the field dependence on increasing field becomes superlinear to sublinear ($\rho \propto H^\tau, \tau = -8.8 \times 10^{-4}$ at $\theta = 0, \tau = -1.6 \times 10^{-4}$ at $\theta = 45^0$). At 300 K, $\rho(H)$ is devoid of detectable hysteresis. Also the field dependence in this case remains linear at all angles.

The primary factors that contribute to the low field MR in these systems are the colossal magnetoresistance effect and the tunneling magnetoresistance if the system has a non zero granularity. The explanation in the case of a non-granular film lies in the multidomain configuration model proposed by O'Donnell et al. [4].

At high fields, the magnetization is aligned in the direction of the applied field. But as the field is lowered and then applied in the opposite direction, the magnetization has to reverse at some point. Considering that the reversal will be rapid, one would expect a change in resistivity $\Delta \rho$ due to colossal magnetoresistance (CMR) given as [4]

$$\Delta \rho \approx \rho \left(M_0 + \chi H_{sw} \right) - \rho \left(M_0 - \chi H_{sw} \right) \tag{1}$$

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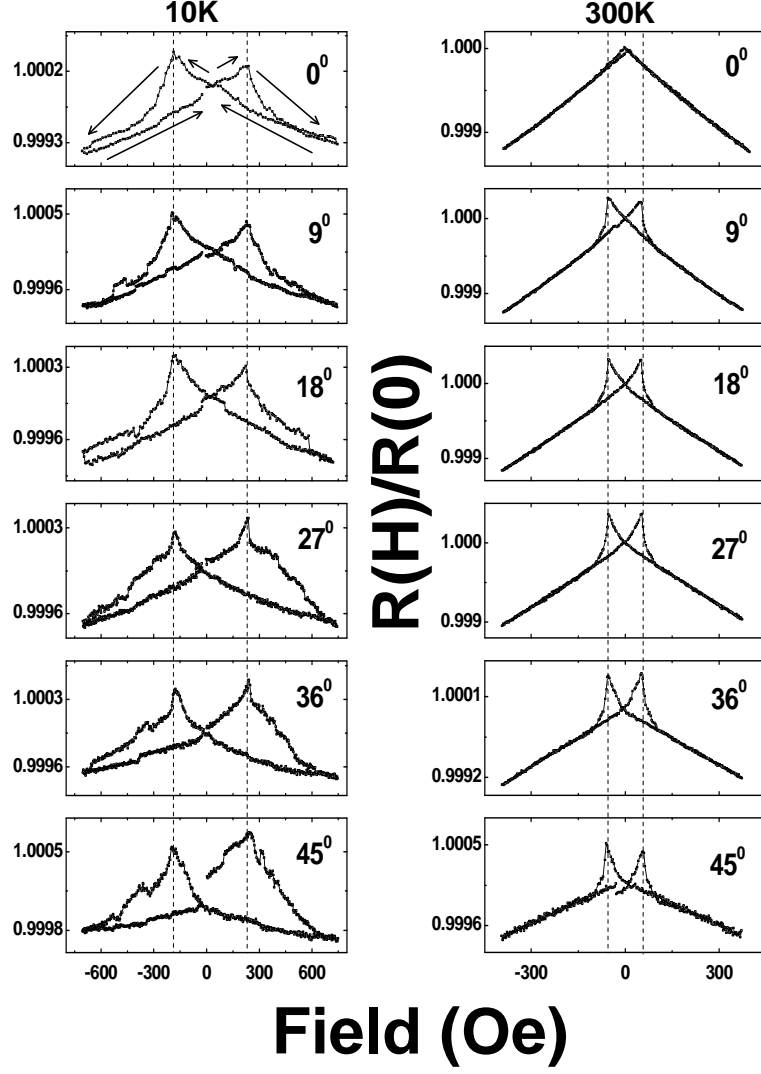
Fig. 1. R(H)/R(0) vs. H data for the [110] sample at 10 K (left panel) and 300 K (right panel) taken at various angles between the applied field and the current direction. The current in this case is flowing along the easy axis, and the hard axis is in-plane and 90^0 to the current direction. Arrows in the figure mark the trajectory followed by the resistance as the field is swept from positive or negative extremities. At 10 K the resistance increases superlinearly as the field reduced from 700 Oe till it reaches a critical negative value H_c. On increasing the field further in the reverse direction, the resistance drop, first rapidly and then gradually. The resistance profile during $-H_{max}$ to $+H_{max}$ field sweep is a mirror image of the $+H_{max}$ to $-H_{max}$ sweep. A large hysteresis is evident in the figure whose area increases with the angle θ between $\vec{H}$ and $\vec{I}$. However the critical field $\pm H_c$ remains the same for all angles within the experimental error (± 10 Oe).

where H_{sw} is the switching field (the field at which the magnetization reversal occurs), M_0 is the spontaneous magnetization and χ is the susceptibility. This change will be seen for a transition in magnetization from antiparallel ($M \approx M_0 - \chi H_{sw}$) to parallel ($M \approx M_0 + \chi H_{sw}$) to the applied field.
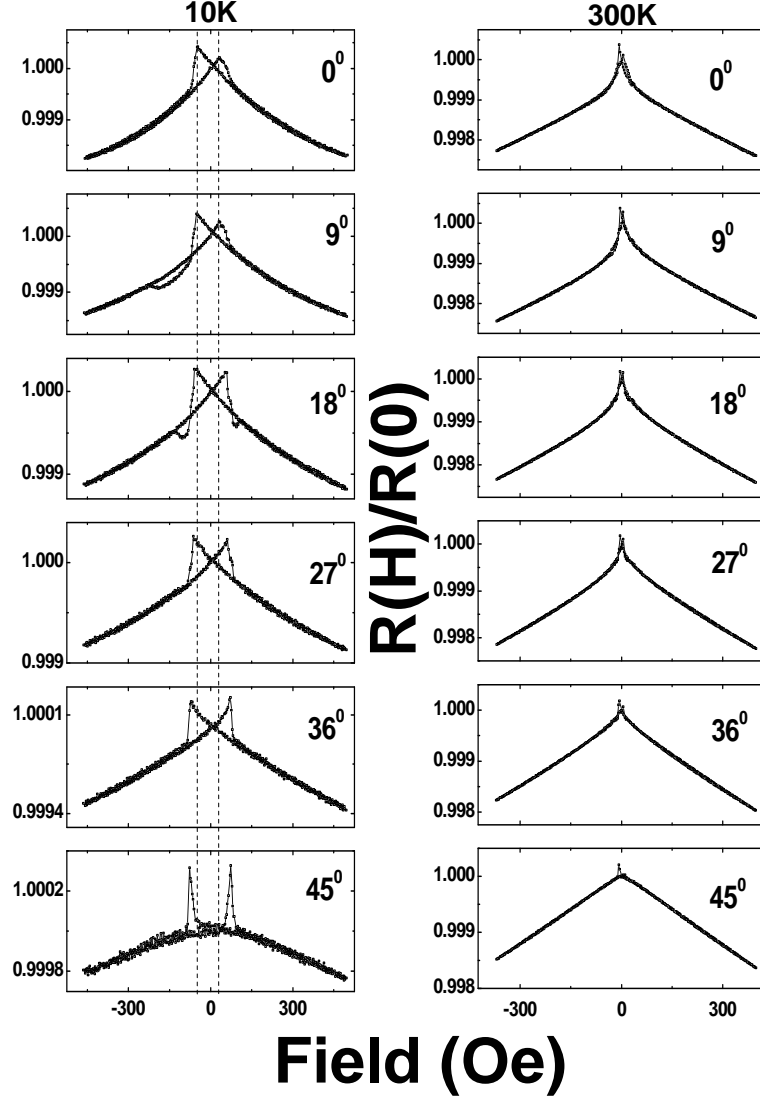
Fig. 2. The isothermal magnetoresistance at different angles between $\vec{I}$ and $\vec{H}$ for the films with [001] orientation for measurements performed at 300 K (right panel) and 10 K (left panel). The current in this case is flowing along the hard axis and the easy axis is 45^0 to the current direction. At 10 K and $\theta = 0^0$, the R(H) curve is mostly reversible except for the twin peaks appearing at $\pm H_c$ which agrees with the coercive field deduced from M-H measurements. On increasing the angle θ (moving away from the easy axis), two interesting features emerge from the data. First, the critical field at which resistivity drops precipitously shifts to higher values, and second, the field dependence on increasing field becomes superlinear to sublinear. At 300 K, $\rho(H)$ is devoid of detectable hysteresis. Also the field dependence in this case remains linear at all angles.

As pointed out by O'Donnell et al. [4], this simple model cannot explain some features in these data. Considering the case when the film is treated as a single domain, the magnetization either flips directly from antiparallel to parallel alignment or it comes to the parallel alignment following a two step process,

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passing from antiparallel, to transverse, to parallel. When $\vec{M}$ is parallel or antiparallel to the applied field one has,

$$\left|\vec{M}\right| \approx M_0 \pm \chi H \tag{2}$$

and for $\vec{M}$ perpendicular to the applied field, $\left|\vec{M}\right| \approx M_0$ which is independent of H. Below T_c and at very low fields, one can assume that $\chi H \ll M_0$ for a single domain sample. So in this case the linear approximation of eq. 2 is correct. So the CMR below T_c is a first order expansion in the small parameter χH about $\rho(M_0)$. From these arguments and taking into account that the CMR is linear, the change in resistivity upon flipping of the magnetization from antiparallel to parallel expressed by eq. 1 can be approximated to

$$\Delta\rho = 2\chi H_{sw} \left.\frac{d\rho}{dM}\right|_{M_0} \tag{3}$$

The single-domain model also fails to explain the deviation from linearity. To overcome the shortcomings of the single domain model, O'Donnell et al. [4] proposed a multidomain-model. In this model, the magnetization reversal proceeds via motion of the domain walls. The resistivity for a sample with the applied field along the easy axis can be written as [4]

$$\rho \approx x\rho_{par} + y\rho_{antipar} + z\rho_{transverse} \tag{4}$$

where $\rho_{par}, \rho_{antipar}$ and $\rho_{transverse}$ are the resistivities of the domains parallel, antiparallel and transverse to the applied field.

Now, the MR data is analyzed in the light of the multi-domain model taking into account that [110] LSMO films show uniaxial and [001] films show biaxial anisotropy. Looking at the data for [110] samples at 300 K (right hand panel of fig. 1), no discontinuous change in resistivity when $H\|I$ is seen. So it looks like that as soon as the field is reversed, the magnetization also reverses. For other angles, a clear discontinuous change is seen. This behavior can be understood by arguing that as the field is slowly increased from zero, the moments align along the hard axis that is perpendicular to the current and as a result, the resistivity increases. Once the field crosses a threshold limit, the magnetization flips abruptly towards the applied field direction. Since T=300 K is very close to T_c for LSMO, it is very weakly ferromagnetic at that temperature. Hence it is possible that for fields aligned along the easy axis no discontinuous jump may be seen. The data at 10 K (left hand panel of fig. 1) show large hysteretic loop in MR. Secondly, the transition is not very sharp. This can be attributed to the deviation from the square hysteresis loop that this sample shows at 10 K[6]. In this case, a transition is also seen for $H\|I$ since at 10 K, LSMO is strongly ferromagnetic.

The R(H)/R(0) curves for the [001] sample reveal some interesting facts as well. If one looks at the data at T = 300 K (right hand panel of fig. 2), a linear R-H behavior when H is parallel to the easy axis (i.e. 45^0 to the current direction) [6] is seen. Some non-linearity sets in once the applied field direction moves away from the easy axis but the non-linearity is not hysteretic. The observed non-linear dependence presumably arises from the slow rotation of the magnetization vector with the increasing external field.

The data at 10 K (left hand panel of fig. 2) show some features of first order transition but the explanation is a little different in this case since [001] samples show biaxial anisotropy. So, when the applied field is along the current direction at low fields, domains aligned in the direction of the easy axis start appearing. Since these domains are aligned away from the current direction the resistance increases. At a particular field, the moments switch to the direction of the applied field and one sees the step in the resistivity. But in this case, the step is also present for H parallel to the easy axis that is 45^0 to the current direction. This can be attributed to the fact that for the field to flip completely, it has to cross two hard directions. So a minimum magnetic energy is required to completely flip the moments.

4 Conclusion

In conclusion it is shown that the anisotropy energy of [110] $La_{2/3}Sr_{1/3}MnO_3$ films is larger than that of [001] $La_{2/3}Sr_{1/3}MnO_3$ films. Further [110] films show larger hysteresis than that shown by [001] films. The data has been analyzed in the light of multidomain model and the behavior seen in [001] and [110] samples can be explained correctly by this model. It is also shown, for both the films the resistivity in the reversible regime is proportional to H^τ, with τ nearly independent of the angle of the applied field for [110] film which is not the case for [001] film.

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